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Neurocognitive mechanisms underlying social learning in infancy: infants' neural processing of the effects of others' actions

Markus Paulus,[1] Sabine Hunnius,[2] and Harold Bekkering[2]
[1]Ludwig Maximilian University, Munich, Germany and [2]Donders Institute for Brain, Cognition, and Behaviour, Radboud University Nijmegen, The Netherlands

Social transmission of knowledge is one of the reasons for human evolutionary success, and it has been suggested that already human infants possess eminent social learning abilities. However, nothing is known about the neurocognitive mechanisms that subserve infants' acquisition of novel action knowledge through the observation of other people's actions and their consequences in the physical world. In an electroencephalogram study on social learning in infancy, we demonstrate that 9-month-old infants represent the environmental effects of others' actions in their own motor system, although they never achieved these effects themselves before. The results provide first insights into the neurocognitive basis of human infants' unique ability for social learning of novel action knowledge.

Keywords: infants; observational learning; neurocognitive processes; ideomotor theory; action-perception coupling

The human ability for the cultural transmission of knowledge is considered one of the reasons for human evolutionary success (Gould, 1979; Habermas, 1985; Tomasello *et al.*, 1993), and numerous classical studies showed that humans acquire relevant action knowledge and skills by social learning (e.g. Bandura, 1986). Importantly, unlike members of other species (for a classical example, see Thorndike, 1911), human infants already possess eminent social learning capabilities in infancy. Striking examples of early social learning are provided by studies on infants' imitation. These behavioral studies show that from early on in life, infants are able to learn from the observation of others' actions (e.g. Barr and Hayne, 1999; Forman *et al.*, 2004; Elsner, 2007; Hauf and Aschersleben, 2008; Hewlett *et al.*, 2011). However, the neurocognitive mechanisms that enable social learning in infancy are yet to be discovered.

One important aspect that humans have to master throughout their lives is to learn about the consequences that particular actions have in their environment and use this knowledge to guide their own actions. To explain the ability to rely on this knowledge, it has been suggested that people acquire bidirectional action–effect associations through repeated co-occurrences between actions and their effects. When they subsequently intend to reproduce an effect or perceive the same effect again, the associated motor program is activated (Elsner and Hommel, 2001; for a recent review see Nattkemper *et al.*, 2010). Following the ideomotor account, such bidirectional action–effect associations subserve intentional action control and thus constitute the cognitive basis of voluntary action (Hommel *et al.*, 2001; Kunde *et al.*, 2007; Hommel, 2009), even though people are often not conscious about these processes (Custers and Aarts, 2010; Kunde *et al.*, 2012).

Research has suggested that already infants (e.g. Elsner and Aschersleben, 2003; Hauf *et al.*, 2004; Verschoor *et al.*, 2010; Paulus *et al.*, 2012) and young children (Kray *et al.*, 2006) learn about the consequences of their own actions by acquiring bidirectional action–effect associations. However, given the relevance of social learning in human development, the question arises of how are infants able to learn about the consequences of others' actions merely through observation (i.e. when they actually never performed this action themselves)?

We suggest that infants can acquire action–effect associations through observation and that this ability might thus form an important neurocognitive mechanism subserving infants' ability for social learning (cf. Paulus *et al.* 2011b). Evidence for this claim comes from behavioral studies showing that infants imitate actions that lead to salient action effects. Paulus *et al.* (2011a) showed that 14-month-old infants imitate an unusual action (turning on a lamp with the head) only when the action is followed by a salient action–effect (i.e. the light effect). Examining younger infants, Hauf and Aschersleben (2008) presented 7- to 9-month-old infants with an experimenter performing two actions on a device. The results showed that the infants preferentially reproduced the action that initially led to a salient action–effect. The authors speculated that infants had acquired a novel action–effect association through observation of another person's action and that this novel action–effect association guided infants' imitation behavior. Yet, more direct evidence is required as these results could partly be subserved by simple stimulus–response learning (Klossek *et al.*, 2008). In other words, following Bandura's (1986) classical differentiation between social learning and behavior demonstration of acquired knowledge, these behavioral studies provide clear evidence for the latter, but leave open which neurocognitive mechanism underlies the former (i.e. social learning).

To investigate the hypothesis that infants can acquire action–effect associations through observation, we conducted a training study with 9-month-old infants, using electroencephalogram (EEG). During a 1-week training period, infants observed on a daily basis how a caregiver played in front of them with a novel rattle that produced a specific sound effect when it was shaken [action sound (AS)]. In addition, they listened every day to a second sound that was presented with a voice recorder [non-action sound (NAS)]. It has been shown that infants of this age are able to smoothly grasp and manipulate objects (von Hofsten and Rönnqvist, 1988) and they should thus be able to relate another person's hand actions to their own motor repertoire (cf. Falck-Ytter *et al.*, 2006; Longo and Berthental, 2006). After the training period, infants' electrophysiological responses to AS and NAS as well as a novel sound [control sound (CS)] were assessed (note that we

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Correspondence should be addressed to Markus Paulus, Ludwig Maximilian University, Leopoldstr. 13, 80802 München, Germany. E-mail: markus.paulus@lmu.de

counterbalanced between infants, which of the three available sounds served as AS, NAS and CS).

If infants indeed acquired bidirectional action–effect associations during the observation of somebody else's rattle action, the perception of the rattle's sound should activate the associated motor program. Importantly, research has provided evidence that cortical motor activation is reflected in a power decrease (i.e. a suppression) in the 6–9 Hz mu frequency band over sensorimotor areas (van Elk *et al.*, 2008; Southgate *et al.*, 2009, 2010; Meyer *et al.*, 2011; Nyström *et al.*, 2011; Reid *et al.*, 2011; for a review, see Marshall and Meltzoff, 2011). The mu frequency band is related to other alpha-like rhythms, but is thought to be an independent phenomenon due to differences in source generation or its reaction to external events (for a review, see Pineda, 2005). For example, in a previous study from our laboratory infants' electrophysiological response to a rattle sound was assessed, which they had learned to actively produce during a training session (Paulus *et al.*, 2012). When infants were subsequently presented with the rattle sound, they showed a stronger suppression of the mu frequency band over central sites compared with when they were listening to two other sounds they had never produced. The fact that infants showed more motor activation when they perceived the sound effect of their previous action provided electrophysiological evidence for action–effect binding in infants. Marshall *et al.* (2011) measured EEG in 14-month-old infants during action observation and execution. The analysis provided evidence for a similar power decrease in the 6–9 Hz frequency band for observed and executed actions over central sites (i.e. cortical motor areas). Reid *et al.* (2011) presented 14-month-old infants with actions they were able to perform with actions outside the infants' motor repertoire or with a baseline condition. The authors reported greater suppression of the mu rhythm for actions within the infants' motor repertoire than for the other two conditions, suggesting that the perception of an action leads to automatic motor activation.

Thus, based on theories that propose that bidirectional action–effect associations subserve intentional action control (Hommel *et al.*, 2001) and based on evidence that infants and young children can learn through the observation of others' actions (e.g. Hewlett *et al.*, 2011; Paulus *et al.*, 2011a), we hypothesized that infants would associate the motor code representing the perceived rattle action with the representation of the perceived rattle sound (i.e. AS). This should be reflected in a stronger decrease in power in the infants' mu frequency band above cortical motor areas for AS compared with the other two sounds.

METHODS

Participants

The final sample consisted of 11 infants (range: 8 months, 25 days to 9 months, 24 days; average: 287 days; 4 boys). Seven infants were tested but not included in the final sample due to equipment failure ($n = 1$), parental interference ($n = 2$) or fussiness (so that too few trials could be collected and/or the data contained strong motor artifacts; $n = 4$). Participants were recruited from public birth records and were healthy, full-term infants without any complications. Informed consent for participation was given by the infants' parents. The families received a baby book or monetary compensation for their visit.

Stimuli

The stimulus material of the training phase consisted of three identical cylindric objects ($d = 4.5$ cm; $h = 6$ cm; see Figure 1) as well as voice recorders (Voicetracer 600, Philips, Germany). The cylindric objects were made out of red plastic and produced three different sounds (due to their content which could be a bell, a couple of metal disks or screws) when shaken. They could thus be used as rattles. Each voice recorder contained recordings from one of the three sounds, so that they could be played to the infants. The voice recorders were inserted into cylindrical plastic boxes that served as containers. This enabled parents to put the voice recorders in a stable position on the table.

The stimulus material of the test phase consisted of different recordings of the same three sounds. Different recordings were included to keep infants' attention (cf. van Elk *et al.*, 2008). Each stimulus lasted for 2000 ms. The auditory stimuli were recorded digitally using a MOTU 828ml2 audio interface on a Mac Pro and an AKG-3000 condenser microphone. Recordings were made in an acoustically isolated room at 16-bit, 44,100 KHz quality. They were controlled for pitch and loudness. Furthermore, to maintain the child's attention and to avoid head movements during in the test phase, geometric shapes were presented randomly as background pictures on a computer screen.

Procedure and design

Training phase

Infants and parents were visited at home and handed over one of the rattles and one voice recorder by the experimenter (see Figure 1). Parents were instructed verbally and by means of a written training schedule about the training procedure. It was indicated that they had to train with their infant every day for about 1 week. They were asked to train 5 min each day with the rattle and 5 min with the voice recorder. The rattle training consisted of shaking the rattle in front of the infants at a distance of approximately 1–2 m (i.e. out of reach). For the training with the voice recorder, the container was placed at approximately the same distance. It was switched on by a caregiver so that the sound was automatically played. In both conditions, infants were either seated in an infant chair or on a caregiver's lap. During the training with the rattle and the voice recorder, parents were instructed to remove any other toys from the infant and to avoid any other sounds in the background (e.g. radio). To ensure compliance with the instructions, parents were asked to confirm the exact training times every day on the printed training schedule and provide information on how their infant reacted to the stimuli.

It was counterbalanced within participants and between days with which object infants started the training (i.e. rattle or voice recorder). It was balanced between participants which of the three sounds was the action-related sound (AS; caused by shaking the rattle), the non-action-related sound (NAS; played automatically from the voice recorder) and CS (not experienced during the training phase).

Test phase

The study was set up as a within-subject design as the participants were presented with all three auditory stimuli. The test session was scheduled 1 day after the last training session in an infant EEG laboratory. To this end, the infant was seated in an infant seat that was placed in front of a computer monitor. The parent was sitting behind the infant. A loudspeaker was located behind the screen. The three auditory stimuli (i.e. AS, NAS and CS) were presented in a pseudo-randomized order (i.e. the same stimulus was never presented more than two times in a row) by the software Presentation 11.07 (Neurobehavioral Systems, USA). In addition, pictures of abstract geometrical figures were displayed on the screen in a random order that was unrelated to the auditory stimuli. Any differences in EEG power between the three sounds could therefore not be due to the geometrical figures. The experiment was conducted until the child lost overt attention, as evidenced by, for example, crying or falling asleep.

EEG was recorded after 1 week of training using an infant-size cap with 30 Ag/AgCl active electrodes (EasyCap, Germany) with a layout following the 10/20 system using a BrainAmp AC amplifier with a

Fig. 1 The objects used in the training phase of the experiment. On the left side is the rattle and on the right side the container in which the voice recorder was inserted.

band-pass filter of 0.1–125 Hz at a sampling rate of 500 Hz. All electrodes were referenced online to a central reference electrode and re-referenced offline to an average over all electrodes.

Data analysis

EEG data were analyzed using Brain Vision Analyzer (Brain Products, Germany). The EEG data were segmented into 2000 ms time frames per trial, as the stimuli were presented for 2000 ms. Trials with artifacts were rejected by means of the automatic artifact rejection function of Brain Vision Analyzer (maximum difference of values in a segment equals 250 mV). To be included in the analysis, infants needed to have at least nine valid trials per condition. Fast Fourier transformations were conducted over each trial, and grand averages were calculated for all three conditions.

On average, 14% of all trials were excluded from further analysis, leaving on average 26.8 trials for each condition per infant. A two-way repeated measures analysis of variance (ANOVA) with the within-subject factors hemisphere (C3 and C4) and sound condition (AS, NAS and CS) and number of included trials as dependent variable revealed only a significant effect of hemisphere, $F(1,10) = 8.226$, $P < 0.05$ (all other Ps > 0.47), showing that more trials were recorded for C3 (mean = 25.9, SE = 2.4) compared with C4 (mean = 27.9, SE = 2.8).

In order to ensure that possible differences in mu suppression between conditions were not due to differences in motor activity, we coded infants' movements from the video recordings (made at 29 Hz). To this end, trial information was assigned to the video recordings during the experiment. The data were analyzed on a frame-by-frame basis for motor activities of the child in each trial (cf. Reid *et al*., 2011). Infants' movement activity was coded for each trial on a four-point scale (0: no movements; 1: low activity; 2: medium activity and 3: high activity) for movements of the hands and for movements of other body limbs. Movement of the hands was included as an extra variable as one could assume that during the training phase the rattle sound was connected to the motor program of the hands so that the perception of the rattle sound could facilitate hand movements. For statistical analysis, data of the two measures (movements of the hand and movements of other body limbs) were entered into an ANOVA for dependent measures with the within-subject factors condition (AS, NAS and CS) and body part (hands and others). This analysis yielded no significant effect (all Fs < 1).

RESULTS

Since we were interested in motor activation in response to the three stimuli, we selected the electrodes C3 and C4 for statistical analysis and averaged the mu frequency power over the 6–9 Hz frequency band (cf. Nyström *et al*., 2011; Reid *et al*., 2011; Paulus *et al*., 2012). Data were entered into a two-way repeated measures ANOVA with the within-subject factors hemisphere (C3 and C4) and sound condition (AS, NAS and CS).

The analysis revealed only a significant main effect of sound condition, $F(2,20) = 6.651$, $P < 0.01$, $\eta_p^2 = 0.40$ (all other Ps > 0.40; see Figure 2A for a topographical representation of the results and Figure 2B for the grand average over C3 and C4). For further analyses, the data were averaged across hemispheres. *Post hoc* paired sample *t*-tests revealed that mu suppression was stronger in condition AS than in conditions NAS and CS, $t(10) = 3.010$, $P = 0.01$ and $t(10) = 3.078$, $P = 0.01$, respectively, whereas no significant difference was found between the latter two conditions, $t(10) = 0.098$, $P = 0.92$.

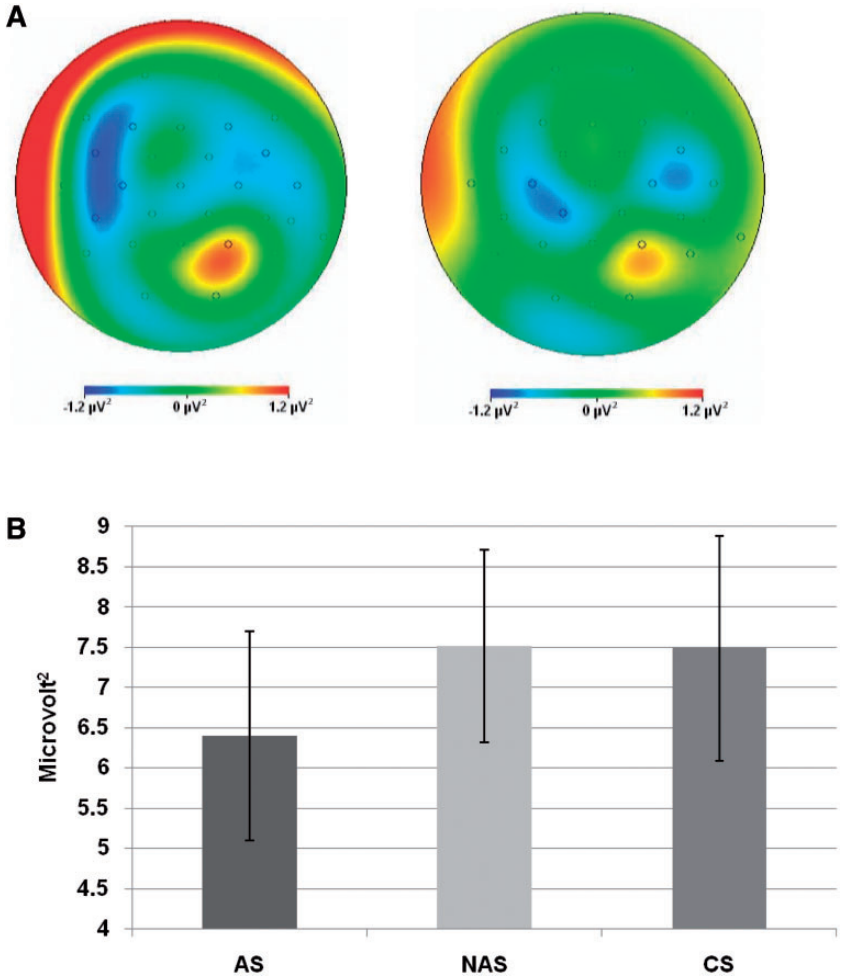

Fig. 2 (A) The topographic maps representing the differences in the EEG power spectrum between perception of AS and NAS (left) as well as AS and CS (right) in the mu frequency band (6–9 Hz). (B) Displays The grand averaged EEG power over the mu frequency band for the three auditory stimuli AS (dark bar on the left), NAS (light gray bar in the middle) and CS (intermediate gray bar on the right) over the C3 and C4 electrode sites. Error bars indicate the standard errors of the means.

This suggests that infants showed greater motor activation when perceiving AS than when perceiving NAS and CS.

DISCUSSION

This study is among the first to examine the neural mechanisms that subserve social learning in infancy. It shows that 9-month-old infants display motor activation when they perceive an effect (e.g. here, a sound) that was previously produced by another person's action, that is even though they never produced this effect themselves. This finding extends previous studies on the impact of infants' own first-hand action experiences on their action perception (Sommerville and Woodward, 2005; Falck-Ytter *et al.*, 2006; Paulus *et al.*, 2012) to the realm of social learning of novel relations between actions and their consequences in the physical world. It provides evidence that human infants represent effects of other's actions within their own motor system and speaks thus to the neurocognitive mechanisms of social learning in infancy.

The results suggest that during the perception of the rattle action, infants were able to relate the other person's movement to their own motor repertoire (i.e. activated the corresponding motor code; motor resonance) and associated the cognitive representation of the perceived effect (i.e. the sound) with the activated motor code and thus acquired a novel action–effect association through the observation of another person's action. Subsequently, the perception of the sound activated the corresponding motor program in the motor cortex (e.g. Elsner *et al.*, 2002; Kohler *et al.*, 2002; Heyes, 2010) and led to the suppression of the mu frequency band (Paulus *et al.*, 2012). The present results therefore provide evidence for the claim that infants in the first year of life are able to acquire bidirectional action–effect associations through observing others' actions and the consequences of these actions in the physical world.

Importantly, our results cannot be explained by differences between the three auditory stimuli, as the use of the three sounds as AS, NAS and CS was counterbalanced over participants. In addition, the fact that mu suppression was significantly stronger for AS compared with another familiar and the unfamiliar sound excludes the possibility that these differences were merely due to a familiarity or a novelty effect. Another alternative account that should be considered is that infants might have been more excited when being presented with the rattle compared with the voice recorder and that this difference might explain the effect. Although we do not have detailed observations of the infants' behavior during the training sessions that took part in the parents' home, we think that it is unlikely that our effects can be reduced to possible differences in excitement during the training. First, we assessed infants' EEG to the rattle sounds after the rattle training and controlled for the impact of movements. Second, if the rattle stimulus would have been indeed more exciting to the infants, we would expect a general increase in brain activity, including, for

instance, areas associated with visual attention. As revealed by the topographic maps though, the differences in activation we found were localized above and confined to cortical motor areas. Notwithstanding this finding, one could argue that infants were more excited during the rattle training and associated this unspecific motor activity with the rattle sound. Yet, research has shown that for action–effect learning to take place, probabilistic contingency and temporal contiguity are very important factors (Elsner and Hommel, 2004). As it is rather unlikely that infants' motor activity was contingent and contingent with respect to the rattle sound (which appeared irregularly according to each parent's individual shaking rhythm), we do not think that our effect can be reduced to differences in infants' motor activity.

Infants were presented with the rattle sound being caused by a hand movement, and consequently we expected the perception of the rattle sound to activate hand-related motor programs. Accordingly, based on findings that a suppression of the mu rhythm at C3 and C4 indicates the activation of hand-related motor actions (Pfurtscheller *et al.*, 1997) whereas central midline activation reflects foot activation (see Marshall and Meltzoff, 2011), we expected an activation of the motor cortex at left and right mid-central sites. In line with this expectation, in a previous study from our laboratory infants' electrophysiological response to a rattle sound was assessed, which they had learned to actively produce with their hand during a training session (Paulus *et al.*, 2012). When infants were subsequently presented with the rattle sound, they showed a suppression of the mu frequency band at C3 and C4. The distribution of activity in this study as evidenced in the topographic maps also displayed a clear mid-central pattern. Given that previous research hypothesized that mid-central activation patterns might reflect the cortical activation of hand-related motor cortex (Marshall and Meltzoff, 2011; Pfurtscheller *et al.*, 1997), the activation pattern of this study could suggest that the perception of the rattle's sound might have led to an activation of the hand areas in the infants' motor cortex. Yet, more research is needed to investigate whether the perception of another person's action elicits effector-specific motor activation in infants.

It should be noted that the topographic maps provide evidence for a clear focus of alpha suppression above cortical motor areas (i.e. mu suppression). This pattern renders it unlikely that our effect was due to differences in visual attention as one could have argued that infants were more inclined to search for the rattle when perceiving the rattle sound. Rather, the distribution of the effect suggests that the difference in the activation pattern was restricted to central sites and thus indicative for motor activation.

Cortical motor activation during action observation has been described in several infant studies providing evidence for the existence of a perception-action matching system early in development (e.g. Southgate *et al.*, 2010; Stapel *et al.*, 2010; Marshall *et al.*, 2011; Nyström *et al.*, 2011; Reid *et al.*, 2011; Paulus *et al.*, 2012). This study investigated whether infants would also show motor activation when perceiving the effect of *another* person's action, i.e. an action that infants never produced themselves. Our findings thus extend this line of research to the realm of social learning and suggest that infants represent the effects of others' actions in their own motor system, even if they never actively produced achieved these effects. They also suggest that action matching and learning about action effects play an important role in social learning. Additional support for this view comes from a studies by van Elk *et al.* (2008) as well as Reid *et al.* (2011) who demonstrated that an observed action, which is not within infants' motor repertoire, does not lead to cortical motor activation. Moreover, directly investigating the impact of action matching and action effects on infants' imitation, Paulus *et al.* (2011a) found that 14-month-old infants were unlikely to imitate an action that was presented in a way they could not relate to their own action repertoire that did not have a salient action–effect.

It remains an open question, though, how infants process and learn from the observation of actions that are outside their own motor repertoire. Interestingly, a recent study shows that infants can learn to simulate another person's tool use actions when they have ample opportunity to observe how the other person handles the tool (Boyer *et al.*, 2011). It is possible that by means of a direct comparison process, infants come to relate the tool to their own hand (Gerson and Woodward, 2012) and are thus able to also learn from actions that are initially not within their own motor repertoire.

This study relates to research suggesting an important role of ideomotor learning and action–effect binding in early development. In particular, it has been suggested that infants' acquisition of action–effect relations plays an important role in the development of action control (e.g. Klein *et al.*, 2006; Verschoor *et al.*, 2010; Paulus *et al.*, 2012) and for an understanding of and learning from others' actions (Baldwin *et al.*, 2001; Elsner and Aschersleben, 2003; Király *et al.*, 2003; Hauf and Aschersleben, 2008; Paulus, 2012). Hauf and Aschersleben (2008), for example, presented 7- to 9-month-old infants with an experimenter performing two actions on a device. The results showed that the infants preferentially reproduced the action that initially led to a salient action–effect. The authors speculated that infants had acquired a novel action–effect association. Our study directly speaks to these findings, as it provides first direct evidence that by the end of the first year of life infants are indeed able to acquire action–effect associations through observational learning.

This study is informative for electrophysiological research on the significance of the mu rhythm (cf. Pineda, 2005). It has been suggested that a power decrease in the mu rhythm reflects cortical motor activation (for a review, see Marshall and Meltzoff, 2011). Although a large body of behavioral tasks with adults (Elsner and Hommel, 2001; Kunde *et al.*, 2002; Kiesel and Hoffmann, 2004) and infants (Verschoor *et al.*, 2010), as well as neuroimaging studies (Elsner *et al.*, 2002; Melcher *et al.*, 2008) provided evidence for cortical motor activation when perceiving effects of one's own previous actions, less is known how the perception of action effects affects the mu rhythm. To date, only one study demonstrated mu suppression for the perception of previously produced effects (Paulus *et al.*, 2012). This study adds to this literature by suggesting that the mu rhythm is not only modulated through observed actions (cf. Marshall and Meltzoff, 2011) but also through the perception of an action's effect, which was previously produced by someone else.

Given the limitations of EEG research with infants (e.g. with respect to the number of possible conditions in a study), this study leaves a number of questions open for future investigations. In particular, one could compare mu suppression for the perception of an action's effect with mu suppression for the perception of the action itself or for the execution of the action and the perception of the action's effect. Such a comparison would allow for the assessment of commonalities and differences in motor activation provided by both stimuli. If one were to find similar electrophysiological patterns for both stimuli (e.g. perception of an action's effect and the perception of the action itself), this would support our claim that the perception of an action's effect activates the same motor program as the observation (or execution) of this action.

Furthermore, following Bandura's (1986) classical distinction between social learning and the behavioral demonstration of acquired knowledge, this study investigated the neurocognitive mechanisms underlying the former. It provides evidence that 9-month-old infants are able to acquire action–effect associations through perceiving others' actions and their effects. Based on previous studies that show that the observation of others' actions and the effects of these actions

affect infants' imitation (e.g. Elsner and Aschersleben, 2003; Hauf and Aschersleben, 2008; Paulus *et al.*, 2011a), we suggest that the social learning of action–effect associations subserves infants' imitation of others' actions. Future research could investigate this claim more directly by assessing infants' behavioral performances and their electrophysiological responses simultaneously when perceiving the effects of a previously observed action. A relation between electrophysiological patterns and imitative performances would provide the strongest evidence for our claim.

Taken together, many studies and theories have suggested that the unique human ability for social learning plays an important role in the evolutionary success of *Homo sapiens* and have pointed to fascinating social learning abilities not only in adults (e.g. Olsson *et al.*, 2007) but also in infants and young children (e.g. Vygotsky, 1978; Gould, 1979; Bandura, 1986; Barr and Hayne, 1999; Hewlett *et al.*, 2011). However, how infants acquire novel action knowledge (i.e. which neurocognitive mechanisms underlie this ability) has remained an open question. The present findings provide preliminary evidence that infants' acquisition of bidirectional action–effect associations through observation might be a key mechanism in the human ability to learn from and imitate others' actions (Paulus *et al.*, 2011a) and might thus form the neurocognitive basis of humans' unique ability for social learning.

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